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Marine transportation risk assessment using Bayesian Network: Application to Arctic waters

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ABSTRACT

Maritime transportation poses risks regarding possible accidents resulting in damage to vessels, crew members and to the ecosystem. The safe navigation of ships, especially in the Arctic waters, is a growing concern to maritime authorities. This study proposes a new risk model applicable to the Northern Sea Route (NSR) to investigate the possibility of marine accidents such as collision, foundering and grounding. The model is developed using Bayesian Network (BN). The proposed risk model has considered different operational and environmental factors that affect shipping operations. Historical data and expert judgments are used to estimate the base value (prior values) of various operational and environmental factors. The application of the model is demonstrated through a case study of an oil-tanker navigating the NSR. The case study confirms the highest collision, foundering and grounding probabilities in the East Siberian Sea. However, foundering probabilities are very low in all five regions. By running uncertainty and sensitivity analyses of the model, a significant change in the likelihood of the occurrence of accidental events is identified. The model suggests ice effect as a dominant factor in accident causation. The case study illustrates the priority of the model in investigating the operational risk of accidents. The estimated risk provides early warning to take appropriate preventive and mitigative measures to enhance the overall safety of shipping operations.

1. Introduction

The vast seaborne trade has permitted an enormous variety of resources to be widely accessible around the world and has thus helped accelerate the world economy. More than 90% of global trade is carried out via sea routes (IMO, 2012) as it is cost-effective. The Northern transport corridor, known as the Northern Sea Route (NSR) in the Arctic region, is one of the potential trade routes connecting major Asian and European ports. The opening of the NSR has reduced shipping distances and fuel consumption as well as emissions (Kitagawa, 2008). According to Schøyen and Bråthen (2011), the distance between a Northwest-European port and the Far East is reduced approximately 40% by using the NSR as an alternative route compared to the traditional route through the Suez Canal.

The presence of sea ice, extremely low temperatures and drifting icebergs has made this region mostly inaccessible for marine transportation and poses threats to mariners and the current ship technologies (Ellis and Brigham, 2009). As the size and number of ships have increased significantly over time (Toffoli et al., 2005), the possibility of shipping accidents in this region is expected to grow (Balto, 2014; Borgerson, 2008). Previous studies confirm that increasing traffic of oil tankers in the Barents Sea will result in a significant number of accidents if further maritime safety measures are not attained (NME, 2011).

A combination of accidental events and processes are recognised as the leading contributors to ship accidents (Yang et al., 2013). Human factors such as human error and visibility are identified as significant contributors to vessel collisions (Fowler and Sørgård, 2000; Khan et al., 2017; Macrae, 2009; Merrick et al., 2000; Van Dorp et al., 2001; Zhang and Thai, 2016). Additionally, human fatigue, lack of technical knowledge of ship systems, poor communication, faulty policies, practices and standards, are significant human-related issues facing the maritime industry (Dhillon, 2007; Talley, 2002).

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The safe navigation of ships, especially in the Arctic waters, is of ultimate concern for researchers as well as maritime authorities. Risk assessment on maritime transportation and risk reduction measures are a part of ongoing studies. However, limited research has been conducted on the effect of both cold and harsh environmental conditions on shipping accidents in this region. This paper proposes a new risk model applicable to the NSR considering the particular environmental and operational conditions to quantify the risk of transit on Arctic routes.

1.1. Literature review regarding existing accident models

In maritime risk and consequence assessment, several methods have been applied to estimate the causation probability. Among the ship accidents, collision has been the focus of many related studies in recent years. Fujii and Shiobara (1971) introduced one of the most common approaches to estimate the number of ship collisions, where the number of collisions is calculated as a product of the number of geometrical collision candidates and a causation probability. Macduff (1974) initially proposed a ship collision and grounding modelling based on available historical accident records. However, it lacked a clear understanding of accident causes. Risk analysis tools such as fault trees are developed to estimate the causation probability of collision event (Abbassi et al., 2017; Pedersen, 1995; Rosqvist et al., 2002). Marine Accident Risk Calculation System (MARCS) is also developed based on fault tree analysis while considering major shipping accidents such as collisions, powered grounding, drift grounding, foundering and fire and explosions by Fowler and Sørgård (2000). Danish institution COWI (2008) proposed formal safety assessment (FSA) methodology for sea traffic taking into account collisions and groundings. Martins and Maturana (2010) applied fault tree analysis to assess the collision and grounding probability using FSA method. Zaman et al. (2014) estimated the risk of collision in the Malacca Strait using the FSA approach. Merrick et al. (2000) developed a Probabilistic Risk Assessment (PRA) technique considering expert judgment to assess the accident risk in the Prince William Sound. Van Dorp et al. (2001) developed maritime accident event chain which included collision, grounding and fire/explosion using the available data combining with expert judgment. Montewka et al. (2010) proposed a geometrical model to assess the likelihood of ship collisions. A collision probability model based on Monte Carlo simulation technique was developed by Goerlandt and Kujala (2011). Later, it was used in evaluating the risk of tanker collisions in the Gulf of Finland (Goerlandt et al., 2011). A probabilistic approach was proposed to assess the risk and sustainability associated with ship collision by Dong and Frangopol (2014). Goerlandt et al. (2015) developed a ship collision alert system to measure ship collision risk based on fuzzy approach and expert elicitation. Banda et al. (2015) visualised the accident risks through a hazard identification model in the Finnish-Swedish winter navigation system. Sormunen et al. (2015) investigated chemical tanker collision as a case study by taking into account data uncertainties. Montewka et al. (2014) proposed BN framework for ship-ship collisions in the open sea, evaluated the probabilities of these events and finally, determined the severity of a collision. Goerlandt and Montewka (2015) developed a Bayesian network model and applied it to a case study of the oil spill from a tanker to quantify the risk. Mazaheri et al. (2016) proposed an evidence-based and expert-supported Bayesian Belief Networks (BBNs) for assessing the probability of ship-grounding accidents. Fu et al. (2016) developed a causal probabilistic model to predict the probability of a ship stuck in ice in the Arctic waters using the BBNs. In this causal model, a set of input parameters such as hydro-meteorological conditions (air temperature, ice concentration, ice thickness, sea temperature, wave height and wind speed) along the analysed route were considered. Khan et al. (2017) proposed an Object-Oriented Bayesian Network (OOBN) model to predict ship-ice collision probability considering navigational, operating and human factors.

1.2. Discussion on existing accident models

Most of the studies discussed above focused on a single accident (Dong and Frangopol, 2014; Fu et al., 2016; Fujii and Shiobara, 1971; Goerlandt and Kujala, 2011; Goerlandt and Montewka, 2015; Khan et al., 2017; Mazaheri et al., 2016; Montewka et al., 2010, 2014; Pedersen, 1995; Rosqvist et al., 2002; Sormunen et al., 2015; Zaman et al., 2014) or combined ship accidents (Banda et al., 2015; COWI, 2008; Fowler and Sørgård, 2000; Macduff, 1974; Martins and Maturana, 2010; Merrick et al., 2000; Van Dorp et al., 2001) and modelling (individual or integrated) of different types of accidents in maritime traffic. However, integrated accident models based on different types of accidents for the NSR are quite limited. Recorded data of wave height and wind speed for the NSR are never considered in the literature or accident analysis. Thus, conventional ship accident models developed for Arctic regions may not address the integrated accident events such as ice-ship collision, foundering and grounding, simultaneously considering recorded data of five sea states. The conventional risk analysis approaches are commonly adopted to identify the propagation of primary causes that may lead to the potential accident consequences. In the quantitative risk analysis, fault tree is used to estimate the probabilities of possible causes of an event and event tree is used to model potential consequences of that event (Meel and Seider, 2006). Additionally, fault trees may be used to find the logical relationship between the primary causes and the potential consequences. However, in this study, BNs are favoured over fault tree analysis due to advantages such as conditional dependency between primary causes and consequences, common cause issues between the linked nodes, the addition of new accident prior probability as well as updating the real-time posterior probability in the model. The advantage of the integrated method is its capability to predict the particular accident considering the environmental and operational factors. This helps to define the accident according to the existing conditions and to take the appropriate mitigative measures to decrease the consequences in advance which enhances overall reliability of the shipping operations.

In reality, it is possible to have an ice-ship or ship-ship collision which may lead to a ship sinking. Ship grounding on the ice may lead to damage to the ship's hull and result in a capsizing accident. However, in the proposed model latter impact of collision or grounding is not considered, with only the causes behind the collision, foundering and grounding and the individual accident probabilities considered. The aim is to show the likelihood of each accident considering most possible causes. It is possible to connect arcs between accident events and show further impact due to those accidents.

The present study aims to develop a novel methodology by using the BN to represent different potential accident scenarios considering the particular environmental and operational conditions to quantify the risk of transit on Arctic routes. Using BNs, the probabilities of three possible accident types on Arctic routes are quantified based on primary causes and their associated probabilities. The methodology relies on historical data and expert judgments in the estimation of the probability distributions of primary events. The primary objective is to reduce the risk of environmental damage to a minimal level caused by ship collisions, while continuously striving to further reduce the risk. Three different accident scenarios that are likely to occur during Arctic transit are studied. A case study which exemplifies the application of the developed methodology is also presented.

2. Bayesian networks

A BN is a specific type of graphical model that is represented as a directed acyclic graph where the nodes represent random variables and

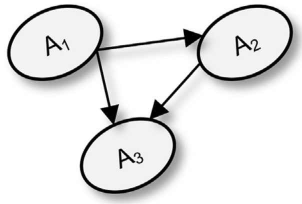

Fig. 1. A typical Bayesian network representing A_1 as root node; A_2 as intermediate node; and A_3 as leaf node.

directed arcs imply local conditional dependencies between parent and child nodes (Ghahramani, 1998; Jensen and Nielsen, 2007; Mihajlovic and Petkovic, 2001; Neapolitan, 2003; Pearl, 1988). In BN, the network structure, the graph, can be observed as a qualitative part of the model, whereas the probability parameters add a quantitative extent to the model (Darwiche, 2009). The joint probability distribution of a set of random variables $U = \{A_1, ..., A_n\}$ based on the conditional independence and the chain rule (Pearl, 1988), is included in the network as:

$$P(U) = \prod_{i=1}^{n} P(A_i|Pa(A_i)) \tag{1}$$

where $P(U)$ denotes the joint probability distribution of variables and $Pa(A_i)$ as the parent set of variable A_i. Accordingly, the probability of A_i is calculated as:

$$P(A_i) = \sum_{U \backslash A_i} P(U) \tag{2}$$

where the summation is taken over all the variables except A_i. A simple BN with a set of dependent random variables A_i is illustrated in Fig. 1 and the corresponding joint probability distribution as: $P(A_1, A_2, A_3) = P(A_1) \times P(A_2|A_1) \times P(A_3|A_1, A_2)$.

Bayes theorem is used in the BN to update the occurrence probability (prior) of events given new observations, called evidence E, to yield the consequence probability (posterior) using the following equation:

$$P(U|E) = \frac{P(U,E)}{P(E)} = \frac{P(U,E)}{\sum_{U} P(U,E)} \tag{3}$$

BNs are favoured over conventional probabilistic techniques as they offer advantages such as (i) BN can be used to model accident scenarios and determine the probabilities of different scenarios using accident prior information; (ii) BN considers the dependency and conditionality of the primary causes and consequences (Jensen and Nielsen, 2007); (iii) the accident information can be updated at any time using the real system data, and (iv) adding a new piece of information in BN requires only a small number of directed edges in addition to a small number of probabilities (Pearl, 1988). BN is a promising method for risk analysis of large and complex systems due to its flexible structure and probabilistic reasoning engine (Khakzad et al., 2013). For example, Hänninen and Kujala (2012) evaluated the ship-ship collision causation model which consists of 100 nodes and 179 links. The application of BN to quantitative risk analysis of offshore drilling operations and marine and offshore accident analysis has previously been discussed by researchers (Baksh et al., 2015, 2016, 2017; Hänninen and Kujala, 2012; Khan et al., 2017; Li et al., 2012; Mazaheri et al., 2016; Montewka et al., 2014; Zhang and Thai, 2016; Zhang et al., 2016). BN model is established based on unwanted events by addressing potential primary causes leading to the unwanted events (ship collision, foundering and grounding in this study), and exploring the possible consequences resulting from the unwanted event.

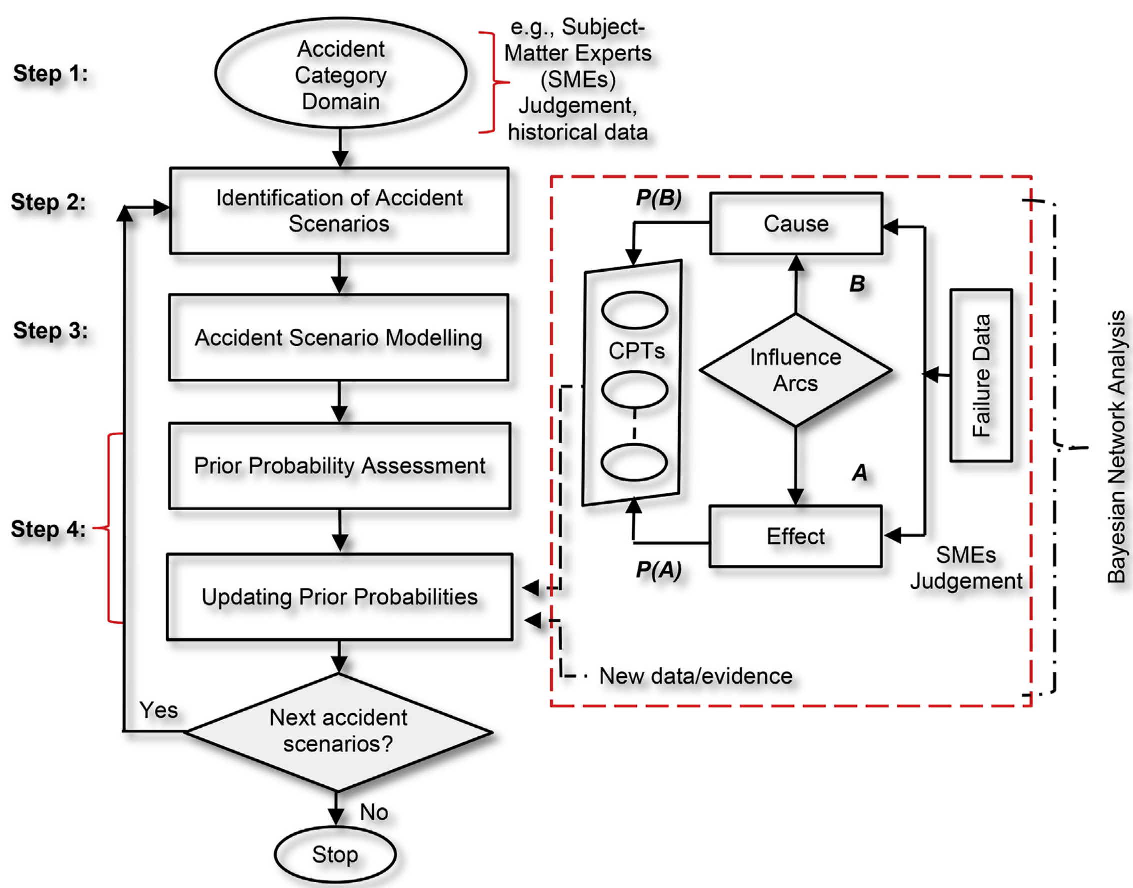

Fig. 2. Developed risk-based methodology for risk analysis in Arctic transit.

3. Proposed methodology for ship accidents in harsh environments

In this study, a BN reasoning process has been developed to provide a natural framework for maritime risk analysis in Arctic transit. A flowchart of the proposed approach is shown in Fig. 2 to ensure a step-by-step systematic process. The entire methodology consists of four steps. GeNIe is used as the robust BN programming environment for the risk modelling and its probability calculations. A brief explanation of each step of the modelling process is given in the following paragraphs.

Step 1: This step heavily relies on historical data and subject-matter experts (SMEs) judgments from the potential sources, such as databases, tests, experiments, simulations, networks and analytical models (Fowler and Sørgård, 2000; Fujii and Shiobara, 1971; Macduff, 1974; Tabri et al., 2009). Any observed data that is available from a specific scenario can be used to update or refine the estimates of previous accident data. In this way, uncertainties and limitations can be reduced in respect of new data or SMEs judgement.

Step 2: In this step of the process, the potential accident scenarios (e.g., collision, foundering and grounding) and associated consequences that can occur in a harsh environment are identified. For example, grounding may occur due to a failure of any of the sub-events (e.g., harsh weather effect, the faults of vessels, navigation failures, visibility issues and tug assistance failure). Further, sub-events such as the fault of the vessel itself can be defined as anchor failure, loss of power in the danger area, or loss of propulsion of the vessel.

Step 3: In this step in constructing the BN, the graphical representation is crucial as it indicates the relevant variables (nodes) and dependencies (arcs). It helps to determine the level of detail that needs to be used in subsequent models. Also, it provides the reasoning for analysing and communicating causal assumptions, which is not easy to express using standard mathematical notation (Pearl, 2000). For example, if there are two events A and B (A as a cause event and B as an effect event), these two events can be labelled and mapped into the network. An arc can be placed between an influencing node (parent) and an influenced node (child) to determine influence relationships between these nodes (Eleye-Datubo et al., 2006). The terminating arrow of the arcs can be set to point to the child nodes.

Step 4: In this step, a set of input parameters based on environmental and operational conditions are assigned. The BN is used to show the causal relationship between the linked nodes. The Bayesian inference consists of computing the conditional probabilities with the BN; that is, to specify the states for each child node and input values for parent nodes in a conditional probability table (CPT). Prior evidence can be entered into the model by manually setting probabilities in the network. The Bayesian inference is enabled via the Bayes formula. Once the prior information is provided in the directed graph, the entered evidence propagates in both directions. The updating belief is computed after prior evidence is entered to improve the prior knowledge, and thus the prior probability values, are updated by calculating posterior probabilities. At any part of the analysis, if it is required to see the contribution of different factors in the causation of an accident, backward analysis can be considered. Regarding newly available data, the calculated posterior probabilities can be considered as the new prior probabilities for future risk assessment. BN simulation software GeNIe is used to estimate the posterior probabilities as well as updating the prior knowledge.

3.1. Accident probability analysis: scenario-based modelling

In this accident scenario modelling, the collision of a ship with Arctic ice during Arctic transits has been taken into consideration. The characteristics of Arctic transits and environments are different and unique compared to local waterways. Therefore, particular factors might have a significant influence on the risk associated with marine navigation in the Arctic waters, such as pack ice effect, environmental obstacles, the combined effect of wind and wave, and emergency assistance. However, detailed investigations of Arctic routes are out of the scope of the present study. Most vessels sailing through the NSR will require icebreaker escort (ABS, 2014). In this accident scenario, it is anticipated that an icebreaker escorts a ship by making channels in the ice. The failure of the icebreaker

Fig. 3. The northern transport corridor with ice and water.

Table 1
Average ice area (million km^2) in the marginal seas of the NSR regions during the period of the seasonal maximum (March) and minimum (September) (Zakharov, 1997).

Sea	March (million km^2)	September (million km^2)	Seasonal Changes (%)
Chukchi	5.95E-01	1.96E-01	67
East Siberian	7.70E-01	5.16E-01	33
Kara	8.30E-01	2.66E-01	68
Laptev	5.36E-01	1.96E-01	63
Barents	8.55E-01	1.28E-01	85

to remove ice may lead to an ice-ship collision. As the traffic on the NSR may increase in future decades, another marine vessel's fault can be considered in ship-to-ship collision scenarios.

Different consequences can take place regarding a ship collision. If it is an oil tanker, the breach in the vessel's hull can propagate a massive spill of hydrocarbons into the sea with the impact being significant damage to the marine environment, economic losses as well as a costly recovering process (Dave and Ghaly, 2011; Goerlandt et al., 2012). The release of hydrocarbons may subsequently lead to different credible accidents such as vapour cloud explosion (VCE) and pool fire (Assael and Kakosimos, 2010; Baksh et al., 2016, 2017; CCPS, 1994; Crowl, 2010). The consequences are inevitable and may cause many fatalities and the loss of the entire vessel if the release of hydrocarbons and fire cannot be controlled and extinguished promptly (Dave and Ghaly, 2011). In harsh and cold environments, emergency responses and evacuation procedures are always challenging for rescue vessels and the crews as they may be delayed due to maneuvering through ice-covered waters (Verny and Grigentin, 2009). These factors may also lead to severe consequences on Arctic routes and need to be considered in the consequent analysis of ship accidents. Due to the potential consequences caused by the cold and harsh environment, it is vital to identify the future risk of ship collision with regards to the increase in ship traffic in this region (Balto, 2014). The geographical map of the northern transport corridor in the Arctic region is taken from the Arctic portal (Arctic-Portal, 2017) with the route through five seas drawn with a dotted line as illustrated in Fig. 3.

3.2. Dynamic ice-ship accident modelling on the NSR

Dynamic risk assessment method takes advantage of case scenario data and updating mechanisms to reassess the risk regarding new information (Khakzad et al., 2012). In Bayesian updating approach, new data are employed in the form of likelihood functions to update prior probabilities using Bayes' theorem (Kalantarnia et al., 2009; Kanes et al., 2017; Kelly, 2011; Meel and Seider, 2006). In this present work, a dynamic risk-based model is developed to analyse shipping accidents on the NSR and reduce the risk of accidents. The model is capable of updating the results whenever new evidence is available during the operation. Although the time slice is not considered within the model, the observations (e.g., new data) however, can be a function of time.

The proposed model will estimate the collision, foundering and grounding probability considering harsh environmental conditions and would be suitable for Arctic region transits. In the proposed model, a ship collision with ice in the Arctic region plays a central role. However, it is recognised that accident type, such as ship foundering and grounding, also has the potential to take place. Therefore, while the development of

Table 2
Mean value of probabilities for primary causes of ship collision, foundering and grounding received from historical data and SMEs judgement.

Index	Basic events	Chukchi Sea	East Siberian Sea	Laptev Sea	Kara Sea	Barents Sea	Data source
	Event	Region 1	Region 2	Region 3	Region 4	Region 5	
X1	Human factor failure	2.97E-04	3.50E-03	1.30E-03	4.00E-04	3.00E-04	SME
X2	Radar failure	2.04E-04	4.00E-04	2.00E-04	5.30E-04	3.50E-04	SME
X3	Environmental obstacles	4.33E-04	2.30E-04	1.90E-04	3.50E-04	2.90E-04	SME
X4	Mechanical failure	6.71E-05	6.00E-05	5.50E-05	5.00E-05	5.50E-05	SME
X5	Operational failure	2.54E-05	3.54E-05	2.14E-05	2.11E-05	2.90E-05	SME
X6	Contaminated fuel in bunker tanks	3.00E-05	2.10E-05	1.30E-05	1.90E-05	1.30E-05	SME
X7	Contaminated fuel measuring system fail	3.30E-05	5.30E-05	4.10E-05	3.10E-05	4.30E-05	SME
X8	Engine fails to operate	2.04E-04	3.00E-04	2.34E-04	5.30E-04	3.30E-04	SME
X9	Basic failure of the propeller	2.03E-04	2.30E-04	3.00E-04	4.03E-04	3.00E-04	SME
X10	Power failure	3.50E-04	5.00E-04	4.10E-04	3.30E-04	4.50E-03	SME
X11	Back-up power failure	1.54E-04	1.74E-04	1.59E-04	1.74E-04	1.66E-04	SME
X12	Map location not updated	1.04E-04	5.30E-04	2.11E-04	3.00E-05	1.01E-04	SME
X13	Digital chart error	3.52E-04	3.30E-04	3.00E-04	5.30E-04	4.00E-04	SME
X14	Navigator malfunction	4.48E-05	4.00E-05	3.50E-05	7.00E-05	3.00E-05	SME
X15	Inappropriate route selection	1.62E-04	3.30E-04	2.00E-04	2.09E-04	3.00E-04	SME
X16	Procedure failure	2.66E-04	1.35E-04	4.00E-04	3.00E-04	3.30E-04	SME
X17	Wind speed	See Table 6	See Table 6	See Table 6	See Table 6	See Table 6	(BMT-ARGOSS)
X18	Wave height	See Table 7	See Table 7	See Table 7	See Table 7	See Table 7	(BMT-ARGOSS)
X19	Pack ice	5.30E-03	3.00E-03	3.70E-03	1.00E-03	1.00E-04	SME
X20	Human error	1.60E-03	3.50E-03	1.30E-03	4.00E-04	3.00E-04	SME
X21	Ridge ice and iceberg	3.00E-04	5.00E-04	3.00E-04	5.00E-04	1.00E-04	SME
X22	Non-detected multi-layer ice	5.10E-04	3.00E-04	5.00E-04	4.00E-04	3.00E-04	SME
X23	Fault of other vessels	3.00E-05	5.00E-05	1.00E-05	5.00E-05	1.00E-05	SME
X24	Ice-breakers failure	2.23E-05	7.30E-04	5.30E-04	2.00E-04	1.30E-04	SME
X25	Insufficient tugboat use	2.09E-04	2.34E-04	3.30E-04	2.30E-04	1.01E-04	SME
X26	Faulty tugboat manoeuvre	6.71E-05	1.35E-04	3.50E-04	3.00E-04	2.31E-04	SME
X27	Not tight enough	6.50E-04	7.00E-04	6.90E-04	6.10E-04	7.00E-04	SME
X28	Structural failure	5.50E-04	6.00E-04	6.00E-04	5.10E-04	5.50E-04	SME
X29	Waterline reaches door	3.33E-04	4.33E-04	4.13E-04	4.03E-04	4.00E-04	SME
X30	Inadequate pumping	4.30E-05	4.90E-05	5.30E-05	5.10E-05	4.99E-05	SME
X31	Leaking	5.50E-04	4.00E-04	5.50E-04	5.00E-04	4.60E-04	SME
X32	Communication failure	6.50E-04	7.00E-04	6.10E-04	6.50E-04	6.90E-04	SME
X33	Faulty design	9.00E-04	1.30E-04	1.10E-04	9.90E-04	1.10E-04	SME
X34	Excessive wear	4.50E-04	6.00E-04	5.70E-04	5.10E-04	5.50E-04	SME
X35	Metal failure	6.00E-04	4.50E-04	5.50E-04	5.10E-04	4.90E-04	SME
X36	Cargo shift failure	4.13E-04	4.03E-04	4.33E-04	4.00E-04	4.11E-04	SME

Table 3
Sample recorded data of wave parameters from the Barents Sea.

Dataset	H_s (m)	T_z (s)	U_{10} (m/s)
1	0.0024	2.8807	1.410116968
2	0.0032	2.8610	0.811585809
3	0.0047	2.8408	0.944581146
4	0.0051	1.7879	2.463794632
5	0.0064	1.8343	2.696691548
6	0.0065	1.8362	2.723586755
..	..	..	..
..	..	..	..
105127	11.3459	11.2784	19.34842017
105128	11.8528	11.3321	19.15760045

ship collision model is in progress, two other accident types, viz. foundering and grounding are also taken into consideration. A digital chart error leads the USS Guardian to misplace the actual location of a reef by about eight nautical miles and resulted in grounding on that reef in the Philippines (Couttie, 2013). However, no evidence has been found of ship grounding due to digital chart error in the Arctic region. This factor is considered due to the USS Guardian tragedy. Quantitative risk analysis of a ship accident requires historical data or expert judgment. In case of missing or limited historical data (to estimate the probabilities of events), the expert judgment is considered (Lindhe et al., 2009). SMEs judgement is utilised where no data are available for a particular type of accident nor the causes of that accident.

In the developed model, three random variables represent ship accidents, such as collision, foundering and grounding. Ship collision is directly/indirectly influenced by twenty primary nodes and twelve intermediate nodes. Similarly, foundering and grounding of a ship are also influenced by seventeen and twenty-two primary nodes, respectively. These primary nodes are used as input information for the intermediate nodes where given probable causes for ship accident, the likelihood of a collision, foundering and grounding, are modelled.

The impact of sea wave height, wind speed and pack ice effect are highly seasonal, affecting both navigation and ship transit. This effect can differ in summer or winter. In winter, icebreakers prepare the narrow channels in Arctic transit which helps the ship to navigate and hence icebreakers impact on ship collision frequency. In the developed model, twelve wave states (e.g., S_{wv1}, S_{wv2}, S_{wv3}, …, and S_{wv12}) are considered which define the wave heights between 0 and 2 m and are profoundly influenced by the wind. For the wind, the first eleven states (e.g., S_{wd1}, S_{wd2}, S_{wd3}, …, and S_{wd11}) are considered to be between 0 and 28 m/s as per Beaufort scale. For example, in the summer season, if the wind speed is in state 6 (8.0–10.7 m/s) which is considered as a fresh breeze, the wave height can be in any state ($S_{wv1} - S_{wv12}$) for that season. Similarly, during winter (December to February) the NSR can be frozen, and therefore high waves on the sea are very unusual. The BMT ARGOSS UK provided the recorded data for different wave height (H_s) and wind state (u_{10}, 10 m above sea level) for the period January 1979 to December 2015 at 3-hourly time intervals (BMT-ARGOSS, 1979–2015).

Different wind speed and pack ice together can make for dangerous icing conditions. However, in comparison to sea wave height and wind speed, icing condition may require a longer time to change from its original state. According to the Meteorological Institute, icing from sea spray will occur at temperatures below −2 °C and with wind speeds more than 11 m/s. Due to the slower formation of sea spray icing and rare, changing conditions, different types of pack ice such as very close pack ice, close pack ice, open pack ice and very open pack ice, respectively can be observed (OCIMF, 2014). The detailed characteristics of the sea ice types have been discussed by previous researchers (Balto, 2014; Bourke and Garrett, 1987; Kum and Sahin, 2015; OCIMF, 2014; Thelma, 2010; Zakrzewski, 1986).

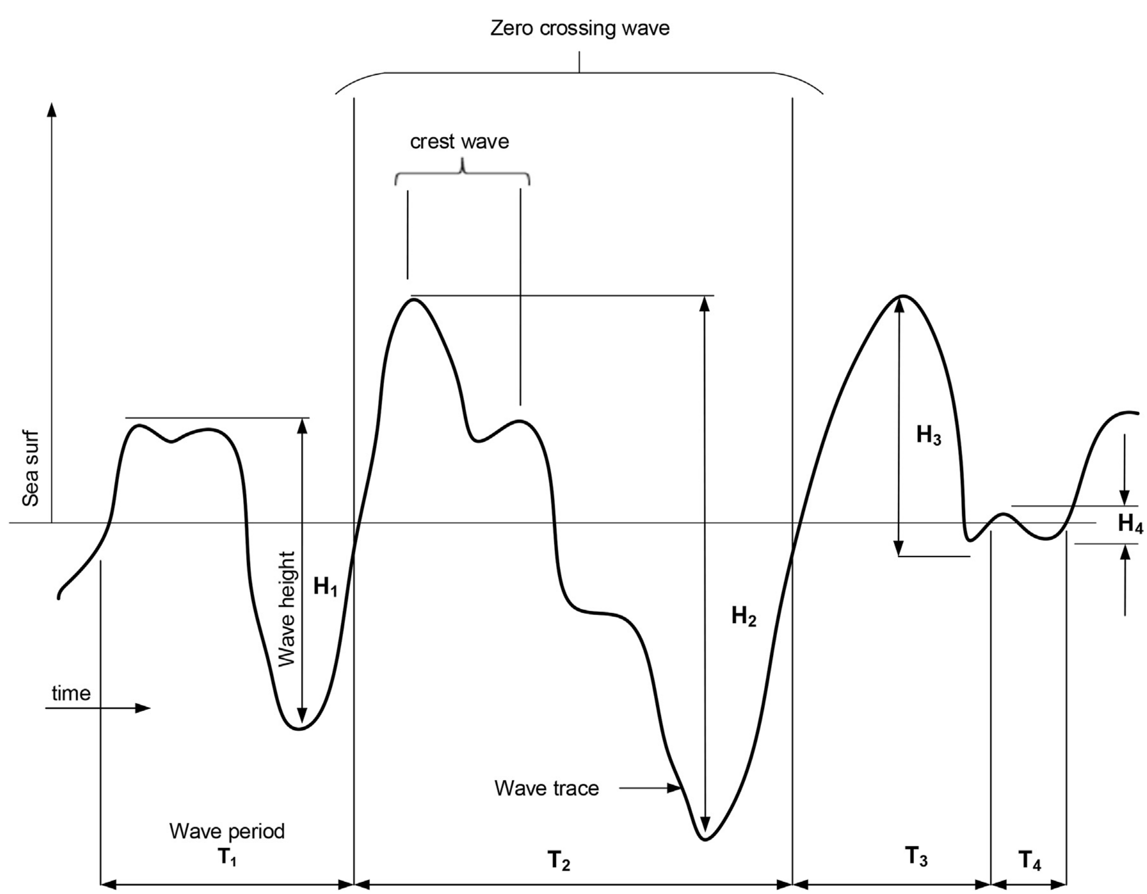

Fig. 4. Zero crossing wave period.

In this study, BNs are used to synthesise expert judgment and recorded data obtained from previous research to perform the integrated analysis. The BN is constructed by primary and intermediate nodes with connected arcs. These nodes have two states only, each with some probability. For instance, "Ice-breakers failure" can be "Yes" or "No", and the probability of the "Yes" or "No" can be determined by historical statistical data. The intermediate nodes are affected by associated primary causes. For instance, the intermediate node "Visibility issues" can be affected by the node "Human factor failure", "Radar failure", and "Environmental obstacles". Taking advantage of the BN, an unwanted event (e.g., collision, foundering, or grounding) is defined and then decomposed to determine its environmental and operational events. The developed BNs for ship collision, foundering, and grounding accident scenarios are illustrated in section 4.1.

4. Application of the methodology: case study

The application of the proposed method is applied to a case study of a ship collision, navigating on the NSR, to estimate the accident probability. The extreme temperature, pack ice, and multi-year sea ice effect and severe climate changes are some of the drawbacks of this region (Kassens, 1994; Melling, 2002; OCIMF, 2014; Thelma, 2010; USA, 1988; Zakrzewski, 1986). These areas are entirely covered with ice during winter and partly covered in summer. According to Johannessen et al. (1997), the presence of multi-year ice on the NSR creates a dangerous environment for marine operations, which subsequently necessitates a more comprehensive method and study to investigate navigational risk and challenges in the harsh and cold environments through the NSR. In the following sections, the application of the proposed methodology is applied to a case study of a ship collision navigating through the NSR.

4.1. The NSR economic viabilities and the associated risk

The Soviet Union developed the NSR shipping route as a major national waterway which has a history of 1306 voyages completed by 331 vessels in 1987 (Ellis and Brigham, 2009). In recent years, the Arctic Ocean has become the dominant hotspot due to its natural resources, shorter navigational routes and pirate free zone. Fossil fuel is a major attraction in Europe to manage the increasing demand for energy. A combined initiative between the NSR and the European explorer is undergoing the extraction of fossil fuel in the Barents Sea, the Kara Sea and the Yamal Peninsula (Pastusiak, 2016; Peresypkin and Yakovlev, 2008). Another growing interest in the eastern region of the NSR for East Asian countries such as Japan and China is the transport of fossil fuel to meet its energy demand (Pastusiak, 2016). An experimental voyage between Yokohama and Kirkenes in 1995 proved the NSR to be a cost-effective route compared to the Suez and Panama Canals shortening the travel time by 15 days and reducing transportation costs by up to $500,000 (Pastusiak, 2016). The NSR would connect the ports of North Asia (Japan, South Korea, and China) and north-western Europe (Hamburg, Bremen, and Rotterdam) and shorten the journey length by about 2500 nautical miles (Verny and Grigentin, 2009). After opening a new container terminal for Europe and Asia, cargo shipping increased on the NSR after 2010, exceeding 3.87 million tonnes of cargo in 2012 and expecting a future increase to more than 5.0 million tons by 2019 (Lammers, 2010; Pastusiak, 2016; Polovinkin and Fomichev, 2012). According to the Arctic Marine Shipping Assessment (AMSA) 2009 report, the estimated volume of oil and gas transportation on the NSR is expected to be about 40 million tons per year by 2020 (Ellis and Brigham, 2009). More economic aspects of Arctic transportation can be found in the literature (Ellis and Brigham, 2009; Hong, 2012; Lasserre and

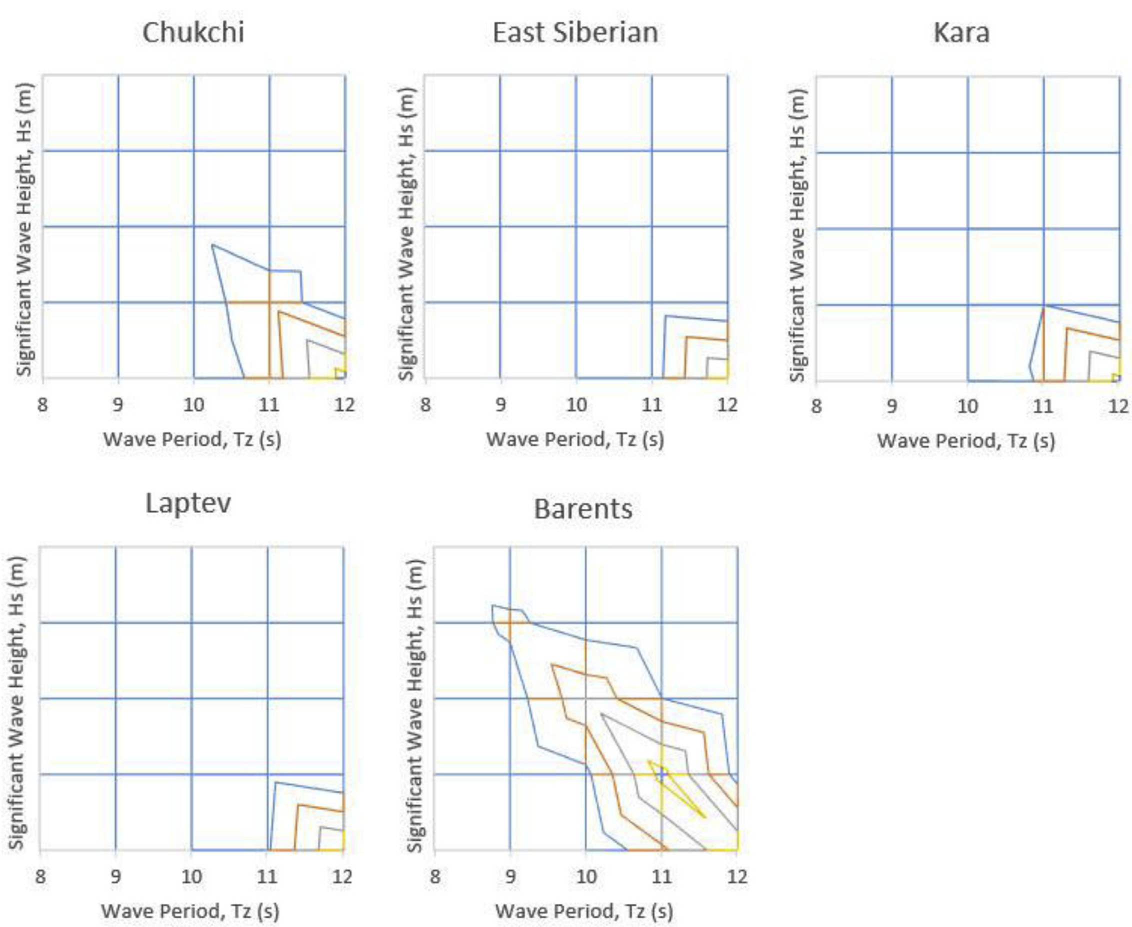

Fig. 5. Linear contour plot of wave height data for each region on the NSR.

Table 4
Scatter diagram for observations of significant wave height and zero-up-crossing period of Barents Sea.

Sign.Wave Ht. (m)	Interval of zero-up-crossing period (s)									
	0 4.0	4.0 4.9	5.0 5.9	6.0 6.9	7.0 7.9	8.0 8.9	9.0 9.9	10.0 10.9	11.0 11.9	12.0 12.9
0–0.9	18946	2960	706	225	101	38	31	13	10	0
1.0–1.9	9084	21487	5048	857	170	58	24	4	6	2
2.0–2.9	3	3778	13441	2526	430	81	15	0	1	0
3.0–3.9	0	7	2444	5889	812	136	21	1	0	0
4.0–4.9	0	0	18	1916	2068	221	26	5	1	0
5.0–5.9	0	0	0	65	1207	423	55	4	4	0
6.0–6.9	0	0	0	0	98	505	56	2	0	0
7.0–7.9	0	0	0	0	5	109	87	4	0	0
8.0–8.9	0	0	0	0	0	6	68	3	0	0
9.0–9.9	0	0	0	0	0	0	14	4	2	0
10.0–10.9	0	0	0	0	0	0	0	3	0	0
11.0–11.9	0	0	0	0	0	0	0	2	2	0

Pelletier, 2011; Pastusiak, 2016).

The NSR consists of the ship sailing routes between the Bering Strait in the east and the Barents Sea in the west (Johannessen et al., 2007). It connects north-western Europe and north-eastern Asia and is considered the shortest sailing route. The NSR is divided into five regions identified as the Chukchi Sea, East Siberian Sea, Laptev Sea, Kara Sea, and the Barents Sea. According to a 50-year series of data from polar stations in these regions and visual observations in open sea areas, it has been observed that ice formation begins in late August in the northern East Siberian Sea whereas, young ice formation starts in the first ten days of September north of the Kara and Laptev Seas (Johannessen et al., 2007). According to Johannessen et al. (2007), young ice appears at the end of the second 10 days of September north of the Chukchi and the Barents Seas. Zakharov (1997) presents an estimate of the average ice area in the NSR regions during March and September as described in Table 1. On average within 35–40 days, the Laptev and East Siberian Seas are entirely covered by young ice whereas it takes about 80–85 days for the Kara and Chukchi Seas (Johannessen et al., 2007). The Chukchi Sea has an area of 6.20E05 km^2 with an average depth of 80 m and is considered as the only route from the Pacific to the Arctic. According to Table 1, an average area of 5.95E-01 million km^2 of the Chukchi Sea is ice covered in March and 1.96E-01 million km^2 in September.

According to Anderson et al. (2011), the East Siberian Sea has a surface area of 8.95E05 km^2 with a mean depth of 52 m which is the shallowest amongst the seas on the NSR. Harsh environment, remote areas, and unexplored maritime areas are some of the characteristics of this region that create challenges for navigational purposes (Münchow et al., 1999). During the winter season, the mean temperature is $-30\,°C$ (Mulherin et al., 1994) and the entire area is ice-covered. However, during summer, 50% of the ice remains. According to the AMSA 2009 report, the entire coastal region along the eastern NSR becomes shallow for all marine operations due to the average depth of the Chukchi Sea and East Siberian Sea (Ellis and Brigham, 2009). The Laptev Sea has an area of 6.50E05 km^2. The average wind speed above the sea surface water is 5 m/s, and storms occur in the sea, three to four times a month. Also, fog is frequent in this region, and the humidity varies between 95 and 98% (Fofonova, 2012). The Kara Sea has the second highest surface area of 8.80E05 km^2 along the NSR with a mean depth of 110 m (Galimov et al., 2006). The Barents Sea has the smallest surface area of 1.40E06 km^2 with a mean depth of 230 m (Sakshaug, 1997; Smedsrud et al., 2010). The winter is considered to be December to February in the Barents Sea when sea ice is relatively thin compared to other regions of the Arctic Ocean. According to a report by Thelma (2010), in extreme conditions, spray and mist can build up four centimetres of ice per hour on the surface of a device in the Northern Barents Sea. The summer season provides an excellent opportunity for marine transportation as the entire Barents Sea becomes ice-free (Sakshaug, 1997).

Maritime transportation poses risks regarding possible accidents resulting in loss of life and ship's cargo as well as detrimental impacts on the marine environment. The accidents on the NSR are comparatively lower than some other regions. The AMSA 2009 report highlighted incidents and accidents which occurred in the Arctic region between 1995 and 2004. According to the report, 293 vessels of different categories were engaged in several accidents including 22 collisions, 68 groundings and 54 damages to the vessel (Ellis and Brigham, 2009). Marine Accident Investigation Branch (MAIB) recorded 65 incidents/accidents between 1993 and 2011 in the Arctic region (Kum and Sahin, 2015). However, only four collisions and four groundings were reported to the MAIB compared to 22 collisions and 68 groundings (Kum and Sahin, 2015). According to Safety and Shipping Review 2014, there were about seven casualties (groundings) in the Arctic region (Review, 2014). Another safety and shipping review in 2016 reported 71 shipping incidents in the Arctic waters during 2015 (Review, 2016). Growing traffic in the Arctic region may increase the risk of ship operations.

4.2. Accident scenario analysis

The cold and harsh environmental conditions have made the Arctic

Table 5
Scatter diagram for observations of significant wave height and wind speed of Barents Sea.

Wind Speed (m/s)	Interval of significant wave height (m)										
	0 0.9	1.0 1.9	2.0 2.9	3.0 3.9	4.0 4.9	5.0 5.9	6.0 6.9	7.0 7.9	8.0 8.9	9.0 9.9	10.0 10.9	11.0 11.9
0–0.2	50	19	3	1	0	0	0	0	0	0	0	0
0.3–1.5	1348	771	141	35	7	3	0	0	0	0	0	0
1.6–3.3	5074	2909	606	184	64	26	1	0	0	0	0	0
3.4–5.4	8729	7372	1852	457	126	49	8	1	0	0	0	0
5.5–7.9	6413	13895	4450	1189	367	81	21	2	2	1	0	0
8.0–10.7	1345	9508	7941	2660	757	214	44	9	1	2	0	0
10.8–13.8	70	2107	4483	3372	1598	503	122	35	5	0	0	0
13.9–17.1	1	158	761	1254	1086	646	295	72	15	3	2	0
17.2–20.7	0	1	38	153	232	215	143	70	46	4	0	3
20.8–24.4	0	0	0	5	18	21	26	16	7	10	1	1
24.5–28.4	0	0	0	0	0	0	1	0	1	0	0	0

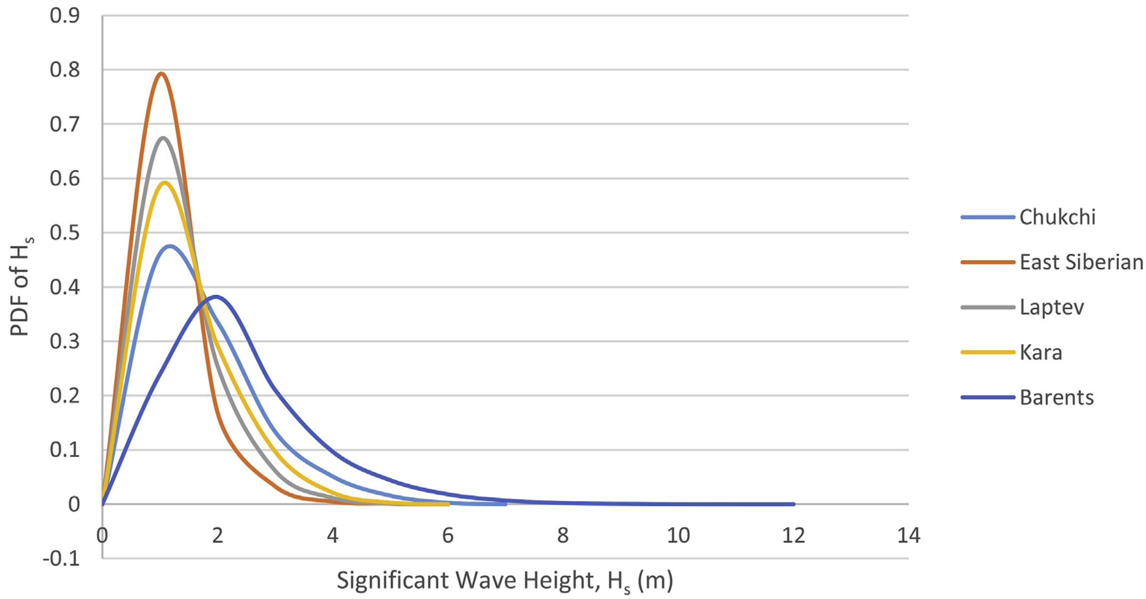

Fig. 6. Probability distribution of significant wave height, H_s for five seas along the NSR.

waters mostly inaccessible as a shipping route. Various factors that can affect the ship's navigation, as well as human performance in emergency situations such as wave height, wind speed, sea current, surrounding temperature, harsh weather effect, and different level of ice along the NSR route, are taken into consideration. However, there are some variations between the values of the environmental factors being identified. Until today, no particular factors have been considered to divide the NSR into different regions. Hence, this route is divided based on the five different seas, the Chukchi Sea, East Siberian Sea, Laptev Sea, the Kara Sea and the Barents Sea respectively.

In this accident scenario analysis, the collision, foundering and grounding probabilities of an oil tanker and the primary causes of these consequences are adopted from previous literature (Antão and Soares, 2006; EMSA, 2009; Noroozi et al., 2014; Trucco et al., 2008; Uğurlu et al., 2015; Yeo et al., 2016) on ship accident modelling in normal conditions. SMEs are being considered if the probability of primary causes specific to Arctic environments is not available.

The severe climate in Arctic regions requires experts to re-evaluate the previous ship accident scenarios when defining the probabilities of the primary causes in this study. The five experts who have more than ten years of research and industry experience in shipping operations (on deck) and are familiar with the Arctic routes environment have been selected to assign the probabilities of the root causes. These experts were male and aged between 35 and 65 (the average age being 51.6). All the experts have their Bachelor (BSc), and Master (MSc) degrees in maritime-related fields. Two experts were working as a master, two as chief-officer, and one as second-officer in Canadian Transport Agency with little or no knowledge of assessment of probabilities. All experts were Canadian and spoke fluent English. These experts were engaged in defining the probability distributions of primary events for each region. The average is the arithmetic mean value for the primary events. The corresponding mean values of probabilities for each primary event for each specific region on the NSR are presented in Table 2.

In this study, most of the input data for the BN analysis in each particular region is received from experts. Based on the prior event probabilities assigned by the SMEs, human error effect on the detection

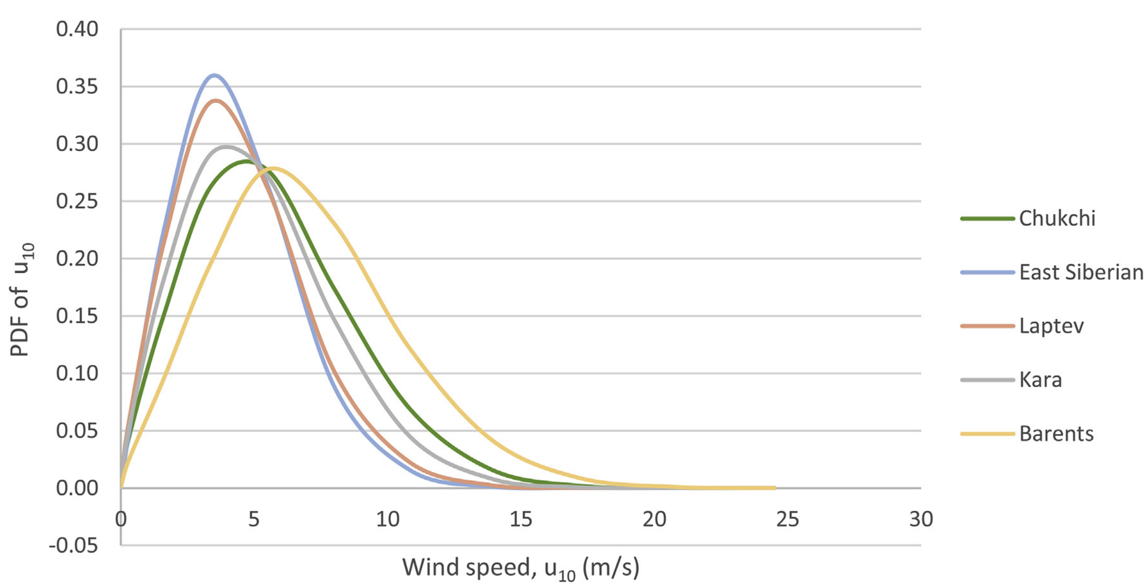

Fig. 7. Probability distribution of wind speed, u_{10} for five seas along the NSR.

Table 6
Probability distribution of significant wind speed for five seas.

Beaufort No.	Scale Description	Wind speed (m/s)	Sea State	Chukchi	East Siberian	Laptev	Kara	Barents
0	Calm	0.0–0.2	S1	2.79E-03	NA	3.02E-03	1.66E-03	7.58E-04
1	Light Air	0.3–1.5	S2	3.35E-02	2.46E-02	4.03E-02	4.20E-02	2.39E-02
2	Light Breeze	1.6–3.3	S3	1.12E-01	1.48E-01	1.41E-01	1.43E-01	9.20E-02
3	Gentle Breeze	3.4–5.4	S4	2.24E-01	3.23E-01	2.77E-01	2.56E-01	1.93E-01
4	Moderate Breeze	5.5–7.9	S5	2.76E-01	3.24E-01	3.13E-01	2.88E-01	2.74E-01
5	Fresh Breeze	8.0–10.7	S6	2.12E-01	1.44E-01	1.70E-01	1.85E-01	2.33E-01
6	Strong Breeze	10.8–13.8	S7	1.07E-01	3.32E-02	4.95E-02	6.89E-02	1.28E-01
7	Near Gale	13.9–17.1	S8	2.90E-02	2.89E-03	5.90E-03	1.41E-02	4.46E-02
8	Gale	17.2–20.7	S9	3.88E-03	3.57E-04	4.64E-04	1.71E-03	9.39E-03
9	Severe Gale	20.8–24.4	S10	2.08E-04	NA	NA	2.72E-05	1.09E-03
10	Storm	24.5–28.4	S11	NA	NA	NA	NA	2.08E-05

failure is recognised as one of the recurrent causal factors for marine ship collision. Previous research suggests that about 80% or more of such accidents involve human error related factors (Rothblum et al., 2002). The cold temperature in a freezing environment can challenge the mariners which in turn may affect surveillance, reaction times, awareness and memory recall, and physical strength (Enander, 1987; Hoffman, 2002; HSE, 2017; Khan et al., 2017; Macrae, 2009; Musharraf et al., 2013; Noroozi et al., 2014). Human factor failure (X1) consists of a variety of sub-groups of errors which can be intended or unintended action of a human. These sub-groups are defined as human performance influencing factors (PIFs) (HSE, 2017). For example, interpretation failure, fatigue/sleeplessness, alcohol abuse can be combined with a human factor failure (Uğurlu et al., 2015). On the otherhand, human error (X20) is considered as an action or decision which was not intended (HSE, 2017). It should be noted that both of these factors are considered as human errors in many available literature. However, to differentiate these factors in the developed BN, human error is considered as a single action on failure to detect ice and iceberg using conventional marine radars and thermal imaging cameras while navigating on the NSR. However, considering all the PIFs would make the accident modelling network complex enough to show the general applicability for the Mariners. Instead, integrating too many sub-factors (contributors to the accidents) into the main factor, the human error and the human factor are considered in the proposed model. Vessel's collision with pack ice and non-detected ice is also considered as another significant factor by the experts in developing the model.

The present study is based on sea wave measurements from the NSR. The measurements were obtained from BMT ARGOSS UK. In BMT ARGOSS, global wind and wave hindcast dataset are available on a grid of spatial resolution 0.5° by 0.5°. The wind and wave parameters were recorded at each grid point, at 3-hourly time intervals, for the period January 1979 to December 2015. The recorded data provided by BMT ARGOSS UK consists of significant wave height, H_s (m), zero crossing wave period, T_z (s) and wind speed measured at 10 m above the surface. A sample of recorded data is shown in Table 3.

A wave is defined as the fraction of a record between two successive zero up crossings (MHL, 2016). In practice, a zero up crossing wave period is considered to occur when the surface passes through the mean line in an upward direction (Tann, 1976). It is the portion of the record between adjacent zero up-crossings. Its height, H is equal to the vertical distance between the highest and lowest point of the wave. Zero crossing wave presented in Fig. 4 is adapted from MHL (2016). Wave data are usually collected for approx. 20 min on each 3rd or 6th hours assuming stable sea states (Skjong et al., 1995). Wave data can be obtained by visual observations from lighthouses, merchant ships and weather ships, however, instrumental observations can be used such as wave buoys, radars, shipborne wave recorders (SBWR), lasers, satellites and surface-piercing instruments (Skjong et al., 1995; Wang et al., 2015). According to the World Meteorological Organization, (WMO, 1983), wave data accuracy requirements are:

$\pm$ 20% for significant wave height and $\pm$1.0s for the average wave period.

According to Tann (1976), significant wave height, (H_s) is defined as the mean height of the highest third of the waves. Given 3N zero up-crossing wave period, the significant height is,

$$H_S = \frac{1}{N}(H_{2N+1} + \dots + H_{3N}) \tag{4}$$

where the heights $H_1, \dots, \dots, \dots, H_{3N}$ are arranged in increasing order (crest to trough heights were used in early research).

The period of a zero-up crossing wave is defined as the time interval between the two zero up crossings which bound it. Given a record of duration t minutes, the mean zero up crossing period is defined as,

$$T_Z = \frac{t \times 60}{\text{No. of zero up crossing waves on the record}} \text{sec} \tag{5}$$

A set of wind and wave data (Total 105128 observations) for the years January 1979 to December 2015 has been obtained based on observations at each grid point for the area of interest from BMT ARGOSS. Linear contour plot in Fig. 5 is plotted using the recorded data from the observations of wave height H_s (m) against wave period, T_z (s) for each sea. The wave data of the Barents Sea is presented as a scatter diagram in Table 4. The wind speed measured at 10 m above sea level for the Barents Sea is also displayed as a scatter diagram in Table 5.

The following equation is used to calculate the probability of signif-

Table 7
Probability distribution of significant wave height for five seas.

Sea State	Wave height (m)	Chukchi	East Siberian	Laptev	Kara	Barents
S1	0.0–0.9	4.61E-01	7.92E-01	6.71E-01	5.86E-01	2.39E-01
S2	1.0–1.9	3.36E-01	1.69E-01	2.55E-01	2.92E-01	3.81E-01
S3	2.0–2.9	1.33E-01	3.30E-02	6.19E-02	9.70E-02	2.10E-01
S4	3.0–3.9	5.12E-02	4.67E-03	1.15E-02	2.13E-02	9.66E-02
S5	4.0–4.9	1.58E-02	1.27E-03	9.94E-04	2.96E-03	4.42E-02
S6	5.0–5.9	2.56E-03	7.92E-05	6.63E-05	3.26E-04	1.82E-02
S7	6.0–6.9	1.67E-04	NA	NA	NA	6.86E-03
S8	7.0–7.9	NA	NA	NA	NA	2.13E-03
S9	8.0–8.9	NA	NA	NA	NA	7.99E-04
S10	9.0–9.9	NA	NA	NA	NA	2.08E-04
S11	10.0–10.9	NA	NA	NA	NA	3.11E-05
S12	11.0–11.9	NA	NA	NA	NA	4.15E-05

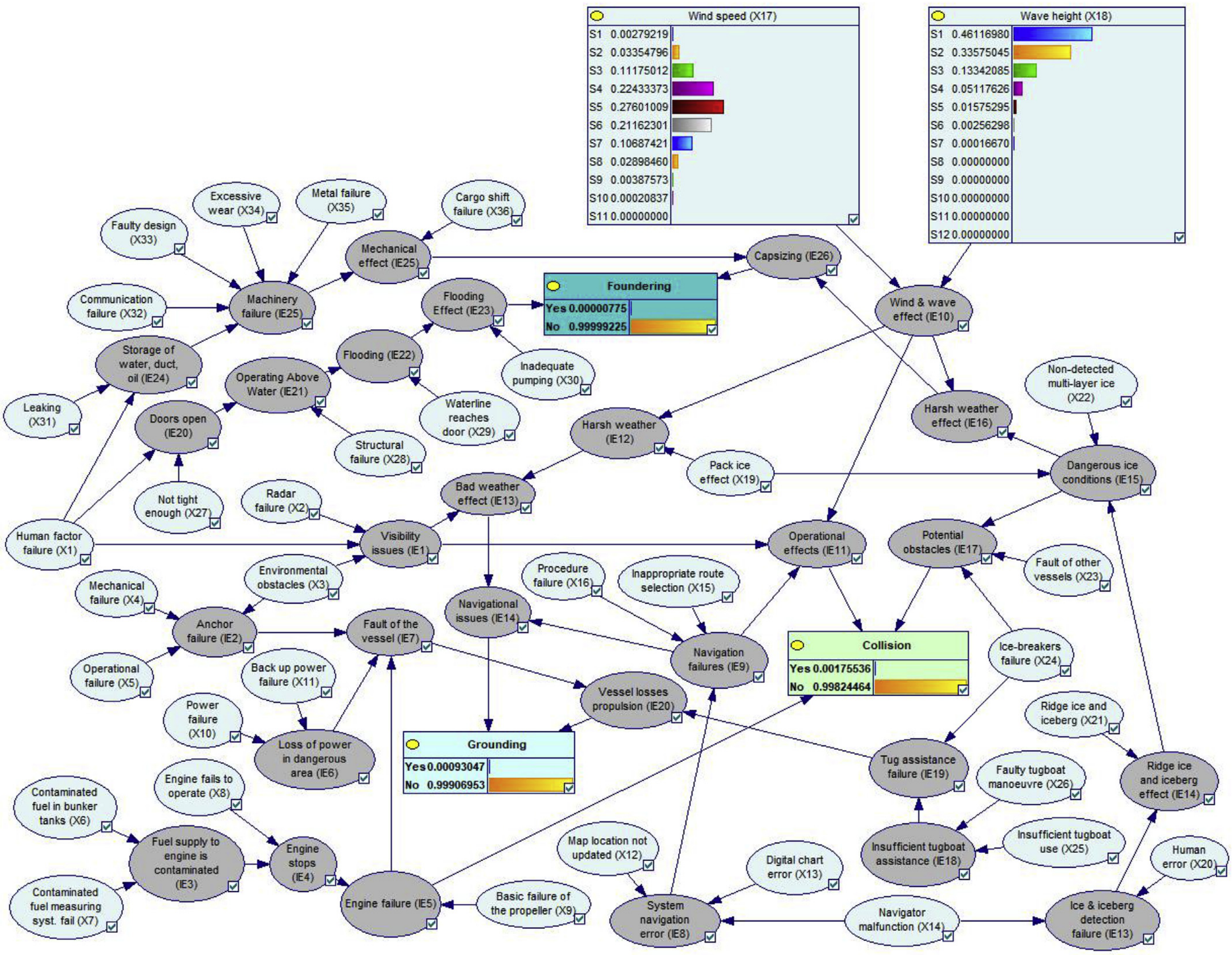

Fig. 8. Graphical representation of the Bayesian network model.

icant wave height, $P(H_s)$ and wind speed, $P\ (u_{10})$:

$$P(H_s) = \frac{\text{Number of wave height occurred in each level (e.g., } 0 \sim 1)}{\text{Total Number of wave height that occurred}} \tag{6}$$

$$P(u_{10}) = \frac{\text{Number of wind occurred in each level (e.g., } 0 \sim 1)}{\text{Total Number of wind that occurred}} \tag{7}$$

The probability distribution of significant wave height, H_s and wind speed, u_{10} for five seas along the NSR are presented in Fig. 6 and Fig. 7, respectively. The probability distribution of significant wave height, H_s and wind speed, u_{10} for five seas along the NSR are presented in Table 6 and Table 7, respectively.

Through a carefully constructed BN, probability data can be incorporated to model the visibility issues, system navigation error, anchor failure, and assistance failure. The combined effect of different kinds of ice in Arctic water is recognised as one of the leading challenges for navigational purposes. The BN diagram for the integrated model of ship collision, foundering and grounding can be developed as illustrated in Fig. 8.

Table 8
Accident probabilities of collision, foundering and grounding on the NSR.

Region	Sea	Collision	Foundering	Grounding
1	Chukchi Sea	1.76E-03	7.75E-06	9.30E-04
2	East Siberian Sea	3.31E-03	1.34E-05	1.37E-03
3	Laptev Sea	2.62E-03	8.96E-06	1.15E-03
4	Kara Sea	2.21E-03	2.43E-06	1.14E-03
5	Barents Sea	1.30E-03	3.11E-07	1.16E-03

4.3. Accident probability analysis

In this study, the potential safety measures to mitigate accidents, such as collision, foundering and grounding and their consequences on the NSR are not considered. The integrated model will help to predict the

Table 9
Risk analysis of ship collision on the NSR in extreme and normal condition.

Regions (Sea)	Conditions (Wind and wave effect)	Collision probability
Region 1 (Chukchi)	Extreme	5.03E-03
	Normal	1.76E-03
Region 2 (East Siberian)	Extreme	5.02E-03
	Normal	3.31E-03
Region 3 (Laptev)	Extreme	5.03E-03
	Normal	2.62E-03
Region 4 (Kara)	Extreme	5.01E-03
	Normal	2.21E-03
Region 5 (Barents)	Extreme	5.01E-03
	Normal	1.30E-03

occurrence probability of any particular accident during ship navigation on the NSR. Different environmental and operational conditions based on case-specific scenarios are identified and considered as primary causes. By applying prior probabilities to these primary causes in the developed model, it is possible to identify most probable accidents that may occur in that region. The results presented in this section are obtained by using the BN model illustrated in Fig. 8. The BN analysis demonstrates the highest collision, foundering and grounding probabilities to be in region 2 (East Siberian Sea) which are 3.31E-03, 1.34E-05 and 1.37E-03, respectively (Table 8).

Similarly, region 5 (Barents Sea) has the lowest probability regarding collision (1.30E-04) and foundering (3.11E-07) events. Region 1 (Chukchi Sea) represents the lowest probability (9.30E-04) regarding grounding event. However, due to extreme wind and wave effects, collision probability is almost similar in all five seas, and foundering probability is higher in region 1 (Chukchi Sea). Likewise, the likelihood of grounding event is higher in region 2 (East Siberian Sea). A comparison of collision probabilities in extreme and normal condition is presented in Table 9.

4.4. Sensitivity analysis

A sensitivity analysis was performed to assess the sensitivity of the BN to some of the most critical variables. From Table 9, it can be seen that a significant change to collision probabilities on the NSR is noticed due to extreme weather condition (severe wind and wave effect). Therefore, any increase or decrease in probabilities of wind and wave effect are not considered in this sensitivity analysis. The main purpose of this study is to determine the factors that mainly contribute to the collision, foundering or grounding scenarios. Therefore, for each of the accidental events, a variation to each of the nodes that presented a higher contribution to the probability of the main event was changed systematically. From the analysis, it can be seen that a significant change in the probability of each node can make a difference to the probabilities of collision, foundering and grounding. A 10% increase in the initial probability of each node can make significant changes to the corresponding accident probability. For collision events, the changes take place for most of the nodes. Similar results occurred when each of the node probabilities is decreased by the same magnitude. For example, an increase of 10% in the probability of pack ice effect, non-detected multi-layer ice, and environmental obstacles made changes of 1.61%, 0.15%, and 0.13% in collision probability respectively. The results of the variation of the probabilities of the collision events when changing each of the initial node probabilities (Chukchi Sea) are presented in Fig. 9.

Based on the sensitivity analysis, we have ranked the major causes of the collision events in the Chukchi Sea, which is shown in Table 10. From the table, it has been shown that the failures of the “Pack ice effect”, “Non-detected multi-layer ice”, “Environmental obstacles”, “Digital chart error”, “Human factor failure”, “Radar failure” and “Procedure failure” impact significantly on ice-ship collision in the Chukchi Sea. The pack ice effect is more significant than the non-detected multi-layer ice in ice-ship collision event (1.61% > 0.15%). Khan et al. (2017) performed a sensitivity analysis for the risk factors involved in the ice-oil tanker collision on the NSR and based on the analysis ranked environmental conditions at rank 3. Severe environmental conditions are the result of high ice and rough weather states. Wu et al. (2005) considered the logistics regression

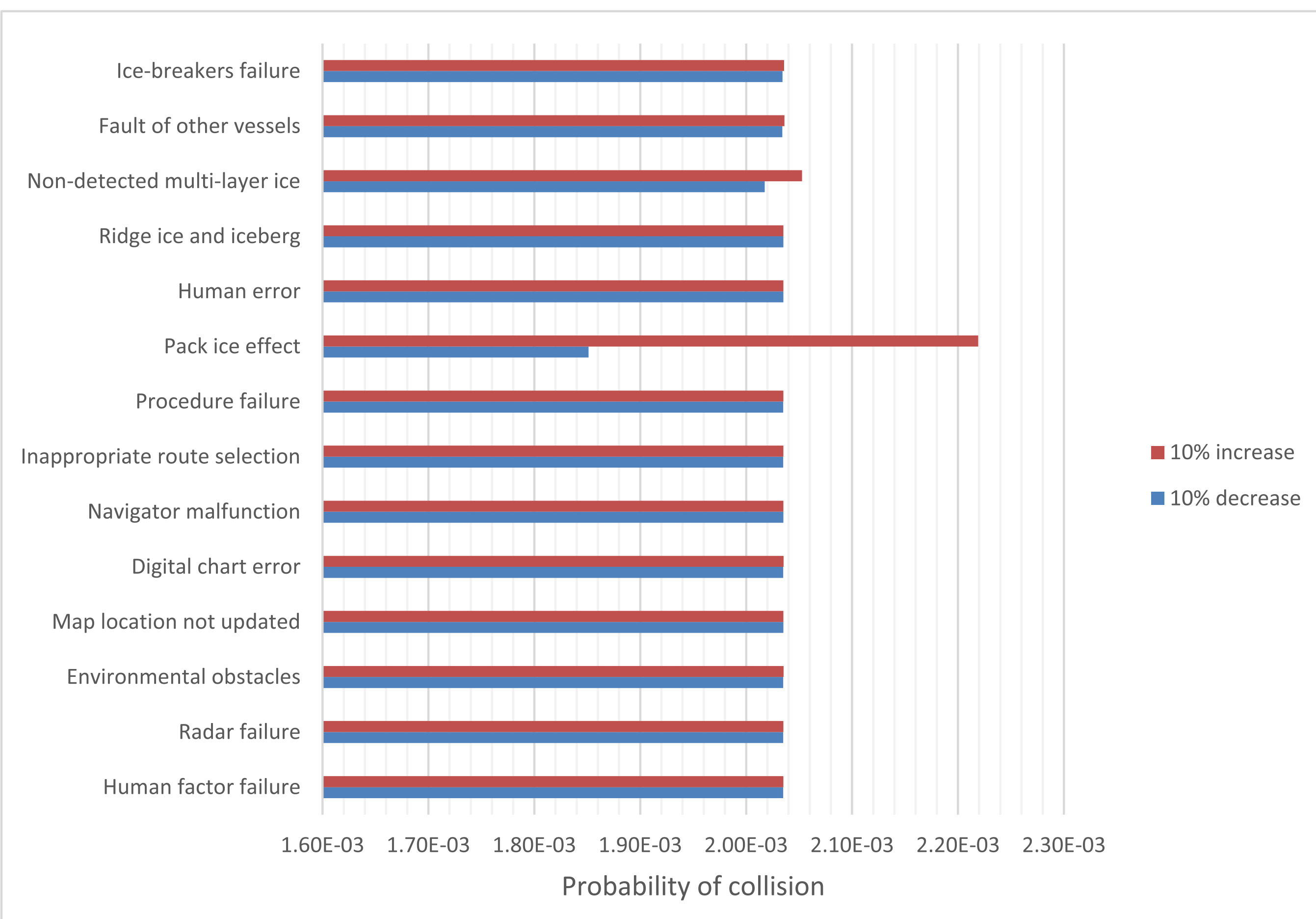

Fig. 9. Sensitivity analysis of collision.

Table 10
Sensitivity analysis for the risk factors involved in ice-ship collision in the Chukchi Sea.

Ranking	Risk Factors
1	Pack ice effect
2	Non-detected multi-layer ice
3	Environmental obstacles
4	Digital chart error
5	Human factor failure
6	Radar failure
7	Procedure failure

model to find determinants of the severity of fishing vessel incidents in the Canadian water. The sensitivity analysis from this model showed increasing severity due to wave height and ice concentration which can affect the stability and mobility of vessels adversely. The above sensitivity analysis allows investigating causes of an ice-ship collision in the Chukchi Sea by narrowing down major factors.

For the cases of foundering event, the effect of pack ice is dominant compared to other accident causes with 0.011%. Besides, increase or decrease of the initial probability of each node represents very little change in foundering probability. In case of grounding, if the probability of digital chart error is increased or decreased by 10%, the probability of grounding will increase or decrease by 0.0035% for instance, an increase from 9.30E-04 to 9.65E-04. Besides digital chart error (Couttie, 2013), other causes such as out of date map location, navigator malfunction, inappropriate route selection and procedure failure may play a more or less significant role in accident causation. The above analysis leads to the conclusion that some of the nodes are highly dominant in all three types of accidents.

5. Conclusion

The existing transportation accident models consider individual events and independent causation factors that may particularly lead to the accidents on the NSR. However, very often an accident is the outcome of non-sequential events caused by combined effects of different factors. Usually, accidents are time-dependent concerning evolving environmental and operational factors. This study focuses on developing a dynamic risk-based model to analyse shipping accidents in the Arctic waters to reduce the risk of accidents considering particular environmental and operational conditions. The proposed method takes the advantages of case-specific data and updating mechanisms to reassess the risk. In the proposed model, ship collisions with ice during navigation in Arctic routes were considered. Other accident scenarios, such as foundering, and grounding were also considered due to the likelihood of their taking place. Application of the developed methodology is reliant on BN modelling, due to the need for reassessing ship accident scenarios in Arctic transits in different conditions. The risk analysis revealed that the East Siberian Sea had the highest probabilities regarding collision, foundering and grounding of the ship. Other regions such as Chukchi, Laptev, Kara and the Barents Sea have almost similar probabilities regarding grounding. However, foundering probabilities are very low in all five areas. The sensitivity analysis of collision, foundering and grounding events also revealed that the developed model was sensitive to several environmental and operational conditions. From the BN and subsequent sensitivity analysis, it is clear that some of the root nodes are the dominant factors towards the accidental event. This contribution is the highest for collision and foundering where an increase of the initial probability leads to a significant change in the probability of the occurrence of accidental events. In the cases of grounding, this effect is less significant. The proposed approach can be helpful for decision makers and safety experts to estimate the probability of different types of marine ship accidents considering the factors most contributing to the existing environmental and operational conditions. The developed methodology can be used to investigate the possibility of preventing and mitigating ship accidents in harsh and cold environments.

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